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Friction Tailored to Your Requirements

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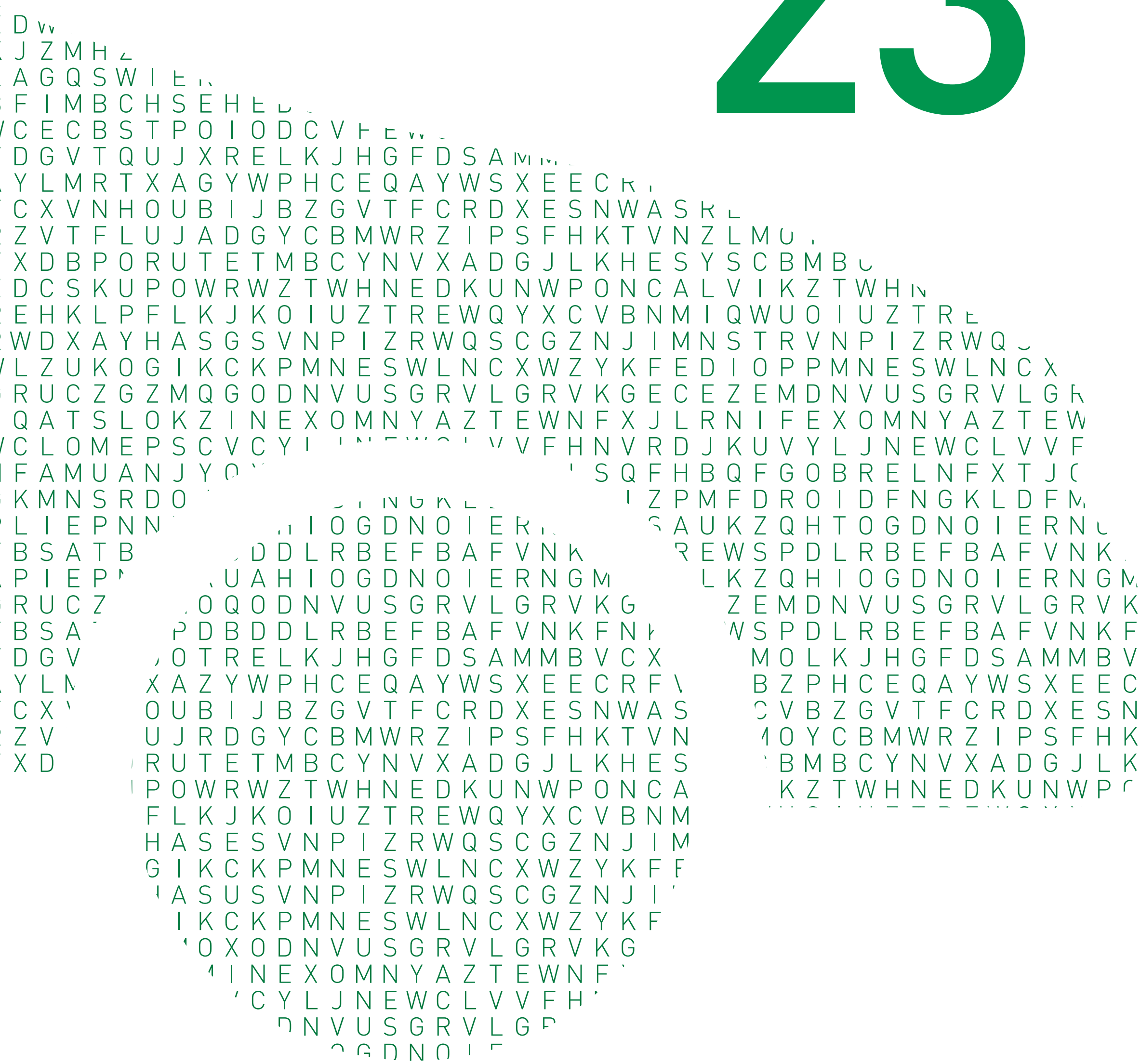

Introduction

In any discussion about reducing fuel consumption, attention quickly turns to powertrain hybridization. However, the fact that a saving of 15 % can be achieved simply by minimizing friction is often overlooked. This has been demonstrated by Schaeffler in various studies over the past few years. The costs required to reduce CO_2 emissions by 1 g/km can be kept well below those of electrifying the drive.

However, friction is not a parameter that must be minimized in every case. Without friction, movement is not possible in our daily lives – and this includes driving cars. Both involve requirements that can only be met if different friction conditions interact in the desired fashion – similar to a classic cross-country skier: The skier hopes that in his tribological system – consisting of the shape of the skis, their sliding layer, and the snow – friction will remain as low as possible when going downhill. By contrast, when going uphill, the skier ideally requires adhesive friction to move up the hill quickly and without having to use too much energy.

Even when seen from a tribological standpoint, the optimization of a system or of an entire powertrain must always be subjected to a cost-benefit analysis and ensure that the functional requirements for the overall system and its components are fulfilled. The service life, for instance, must not be less than that stipulated in the requirements specification. That is why the experts working at Schaefflers' Surface Technology Competence Center depend on the systems expertise available in the company when developing highly specific coating solutions.

Basic principles

Tribological system

System details
According to conventional definitions, a tribological system consists of four elements [1]: The part and the counterpart – these two move relative to each other – and the interfacial medium as well as the ambient medium. Now, new types of coating systems in the micrometer and nanometer range are adding another element that has a significant influence on the properties of tribological systems and that can be used to adjust these systems for a specific purpose (Figure 1).

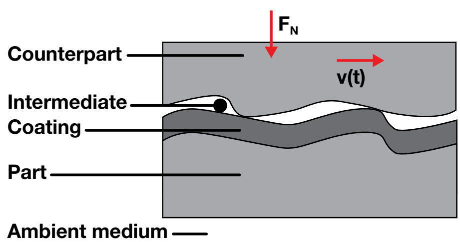

Figure 1 Structure of the tribological system [1]

Friction in tribological systems
The amount of friction that occurs in a tribological system is influenced by a range of factors. In addition to the load applied and the lubricant characteristics, the surface of the active areas is particularly significant. The most important surface characteristics that determine friction and wear include the following [2]:

– The chemical composition of the surfaces that can be changed by pretreatment or during operation by reactive layers on the component surface.

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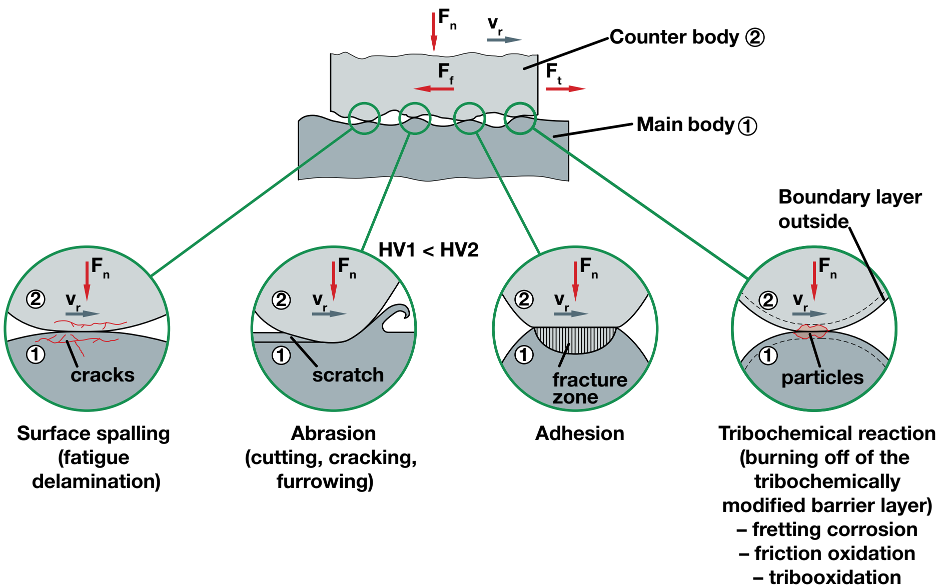

Figure 2 Overview of wear mechanisms

- The hardness and Young's modulus of the materials used. A hard surface alone does not protect a component if the basic material underneath can easily undergo plastic deformation.
- The surface structure not only affects lubricant film formation but also the force applied to the surface and thus surface fatigue.
- Interaction of the surface and the lubricant.

Generally, a distinction is made between four wear mechanisms (Figure 2). Abrasive wear occurs as a result of the mechanical impact of a harder active surface on another surface or hard particles. Adhesive wear results from the molecular interaction when surface contact occurs in the contact interface. Tribochemical reactions change the contact interfaces by oxidation, for instance. Surface fatigue occurs if the material microstructure changes under mechanical stress.

There are various types of friction. The Stribeck curve is a good way to distinguish between the various types, as it can be used to plot the relative motion of the active surfaces for a lubricated contact in relation to the friction torque that occurs (Figure 3).

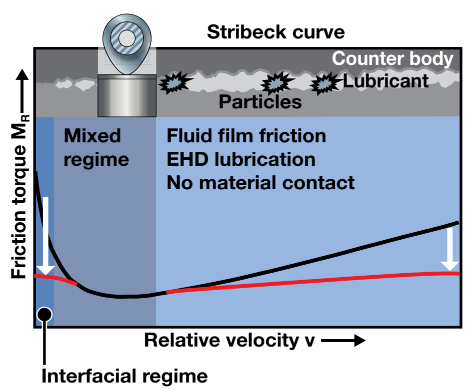

Figure 3 Curve of the friction torque in relation to the relative speed (Stribeck curve). The black curve shows the classic profile, the red curve shows the torque profile when using nano-structured, diamond-like coating systems in the valve train.

Surface technology

In addition to the lubricant, the material and surface quality of a bearing also have significant influence on friction and wear behavior. The properties of the material close to the surface are changed to improve the tribological characteristics of engine and transmission bearings. The initial approach here is to achieve smoothing by reducing the roughness peaks, such as by honing the raceways. Additional improvement can be achieved by changing the surface through heat treatment and coating. Conventional methods here are black oxide finishing and carbonitriding. Chrome-plated surfaces are often used for engine and transmission components that are subjected to high stress levels.

State-of-the-art carbon thin film coating systems usually do not consist of a single layer but of up to 100 layers in the nanometer range that perform certain functions. The exact layer structure is matched to the relevant application and requirements [3].

Analysis, calculation, and simulation

It is not unusual for tribological aggregate loading conditions not to be fully known as part of component development. That is why the services of Schaeffler's Surface Technology Competence Center include a

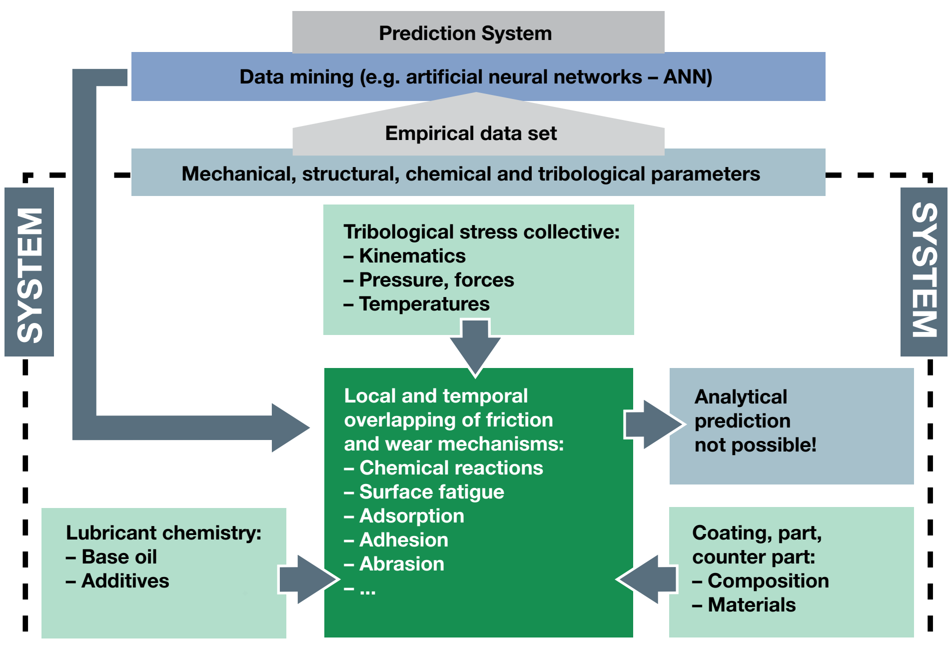

Figure 4 Method for predicting friction based on empirical data [4]

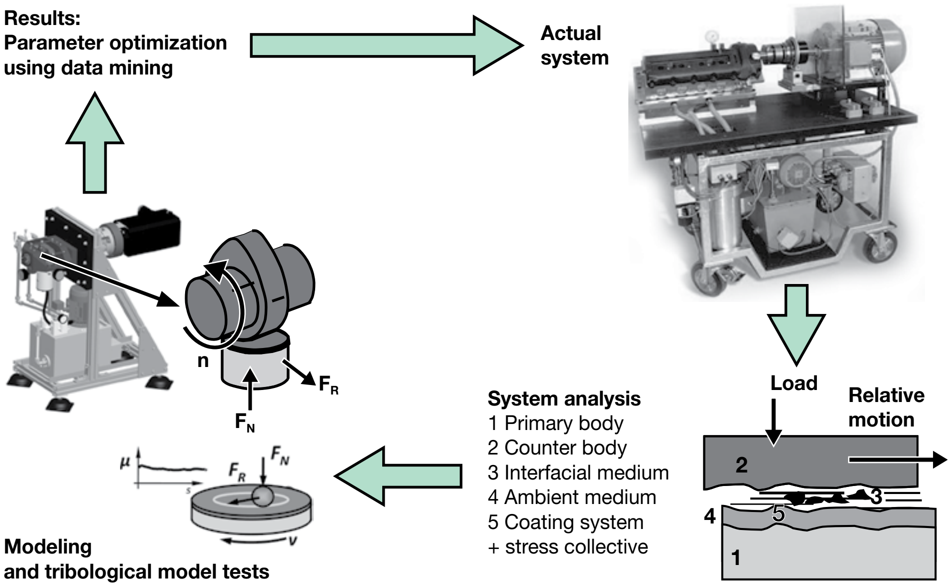

Figure 5 Data mining as part of the development process for coatings [4]

comprehensive analysis of the initial situation. A standardized procedure ensures, for instance, that all relevant parameters are entered.

A good development strategy always takes the overall system into consideration. This is the only way to develop a rolling bearing that is optimally designed for a specific application. Against this background, Schaeffler has expanded its tried and tested Bearinx® calculation program to include an analytical model for calculating rolling bearing friction. This model takes a wide range of parameters into consideration, such as real pressure distribution and internal bearing geometry. In addition to load distribution and service life, it permits the calculation of rolling bearing frictional torque and thus the power loss of entire shaft systems or transmissions.

Schaeffler has been breaking new ground in the development of the tribological system of components that are oil lubricated and coated with customized diamond-like carbon coating systems. Due to the high complexity and interactions imminent to the system, the possibilities for analytically calculating tribological behavior is limited. The development and optimization of coatings for the surfaces of cams and bucket tappets that come into contact with each other has thus so far been based on experimental investigations and the experience of specialists. This method can be time-consuming and expensive.

For this reason, Schaeffler has developed a method that can predict the tribological behavior of camshaft and bucket tappet systems, for example. It is based on a combination of data mining and an artificial neural network and can be practiced with available experimental data [4] (Figure 4).

In this process, the artificial neural network learns the phenomenological correlations on which these data are based.

Their capability to "learn" non-linear correlations allows artificial neural networks to predict an input variable – such as the friction value – even in complex tribological systems. Influencing factors include the type of coating and its hardness, the surface quality, lubricant oil additives and their concentration, the base oil and its viscosity, and the material of the counterbody and its structure.

The suitability of an artificial neural network for this kind of application depends on its predictive accuracy. This is determined by entering data from an experiment that was not used to practice the model. Finally, the prediction is compared to the value measured in the experiment. The data mining process is thus integrated into the development process of coatings for tribological systems (Figure 5).

Although data mining programs already contain automated optimization algorithms, expertise is required to design the optimum network topology of the artificial neural network. The challenge lies in finding the optimum number and arrangement of neurons, the optimum number of input variables, the optimum parameters of the learning algorithm, and much more for specific data with a given number of examples.

Since artificial neural networks only approximate functional correlations in most cases, the evaluation of a learned model is one of the most important steps in data mining. This can be achieved through various methods. Schaeffler has found that a 10x10 cross validation or boot strap cross validation supplies the best results to predict the tribological behavior of a camshaft and bucket tappet system. Upon comparison with an externally driven cylinder head, a deviation of only 8 % was found – a very good result, especially when considering that the measurement error with reference to friction is at 5 % [4].

The use of such methods capable of "learning" can therefore reduce the time and costs spent on experimenting, secure available knowledge and use it efficiently for product development.

Energy efficiency through minimized friction

Influence of bearing designs

The friction occurring on the active surfaces of bearings is primarily determined by the selection of the bearing system and the bearing type and then by its design details. One example here are the bearing supports of the main shafts in the transmission. Locating non-locating bearings are increasingly used as an alternative for conventionally adjusted tapered roller bearings. Schaeffler has analyzed various applications to determine the effect a change in the bearing system can have on fuel reduction. For a compact car with a double clutch transmission, consumption was reduced by 3.8 % in the NEDC simply by changing the bearing system to locating non-locating bearings. Tandem angular contact ball bearings offer significant benefits in the rear axle differential. They replace the tapered roller bearings used in the past and develop a smaller contact surface and thus a lower friction torque while maintaining the same load carrying capacity (Figure 6). With regard to the vehicle, this results in a potential CO_2 reduction of 1.5 % that can be achieved at low cost.

Over the past few years, significant progress has been made by using rolling bearings instead of plain bearings. For in-

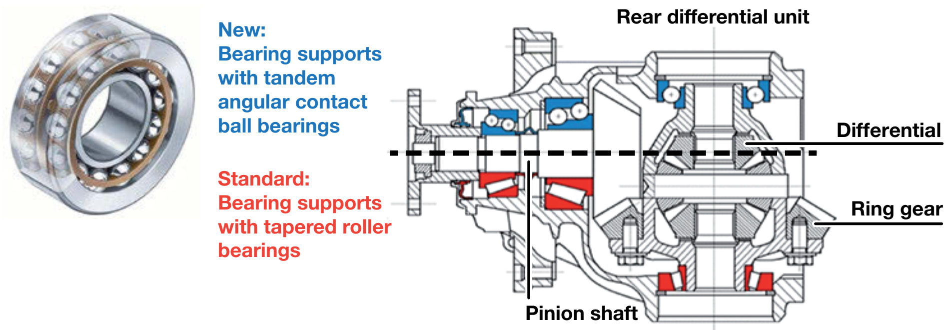

Figure 6 Use of tandem angular contact ball bearings in the rear axle differential (blue) instead of tapered roller bearings (red)

stance, this is true for balance shafts in the engine. Changing to rolling bearings while also designing the components with an optimized weight can reduce CO_2 emissions by up to 2 % at a cost of less than ten euros per shaft. The cost-benefit ratio is just as favorable when switching from plain bearings to rolling bearings in the camshaft bearing supports.

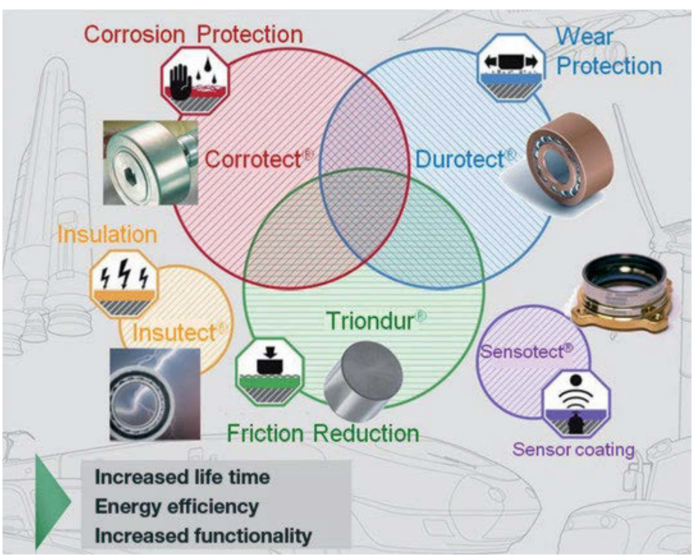

Figure 7 Schaeffler modular coating system as a basis for coatings for specific requirements

Coatings for specific requirements

The Schaeffler Coatings Center uses all of the coating technology methods and has a modular system for validated coatings that can meet any requirement: Corrotect® coatings made from a zinc-iron or zinc-nickel alloy provide corrosion protection, Durotect® designates tribological coatings that are produced chemically. The coating configuration with iron oxide compounds is characterized by the fact that it has good dry running characteristics in the event of insufficient lubrication. Insutect® – which can be used as an aluminum oxide coating, for instance – has been used primarily in energy production for current insulation; at Schaeffler, it is mainly used for railway bearings, generators, and ship engines. With the hybridization of the powertrain, this coating has become more and more important for the automotive industry as well (Figure 7).

Over the past few years, nano-structured coating systems based on carbon have been used increasingly as an alternative for conventional surface technology processes, such as those developed by Schaeffler under the Triondur® brand name. In the power train, this type of coating system was initially used in bucket tappet valve trains because the cost-benefit ratio appeared to be especially interesting: By using a customized Triondur® diamond-like carbon (DLC) layer on the tappet base, the sliding contact surface for the cam, the tribological properties have improved so much that friction in the valve train has been reduced by half. The mechanical bucket tappet thus almost reaches the friction values of a roller finger follower [5]. In relation to the entire vehicle, this means a reduction in CO_2 emissions of 1 to 2 % (Figure 8). Triondur® coating here offers excellent wear protection and hardly requires any design space at all with its layer thickness of only 2 to 3 microns.

Schaeffler has standardized both its coating processes and its coating facilities. The same machines used in volume production are used for new developments or adjustments from the start. The manufacturing process is developed along with the product. This ensures that the transfer from development in the coating process to worldwide volume production is stable and free of errors. The result is a consistently high level of quality irrespective of the manufacturing location.

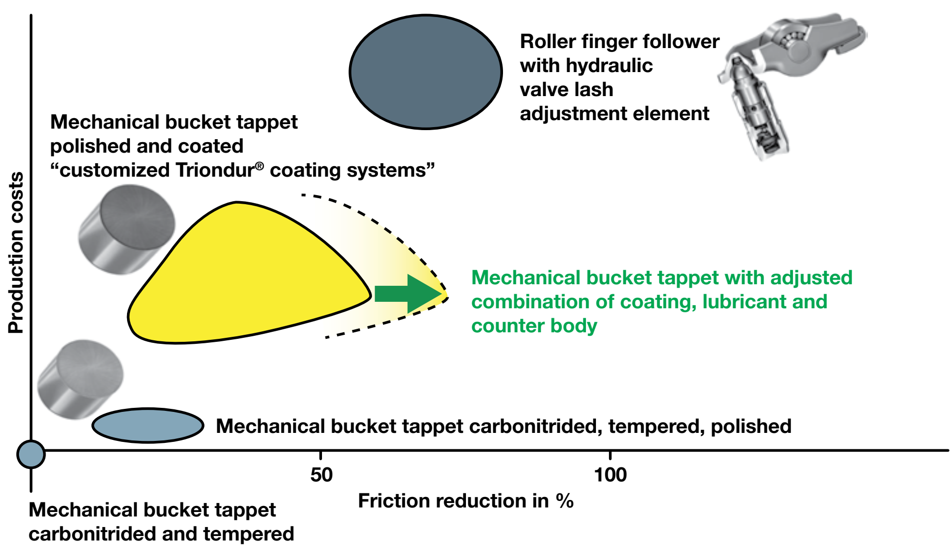

Figure 8 Triondur® DLC coatings improve friction behavior by up to 50 % and offer a high level of wear protection [5]

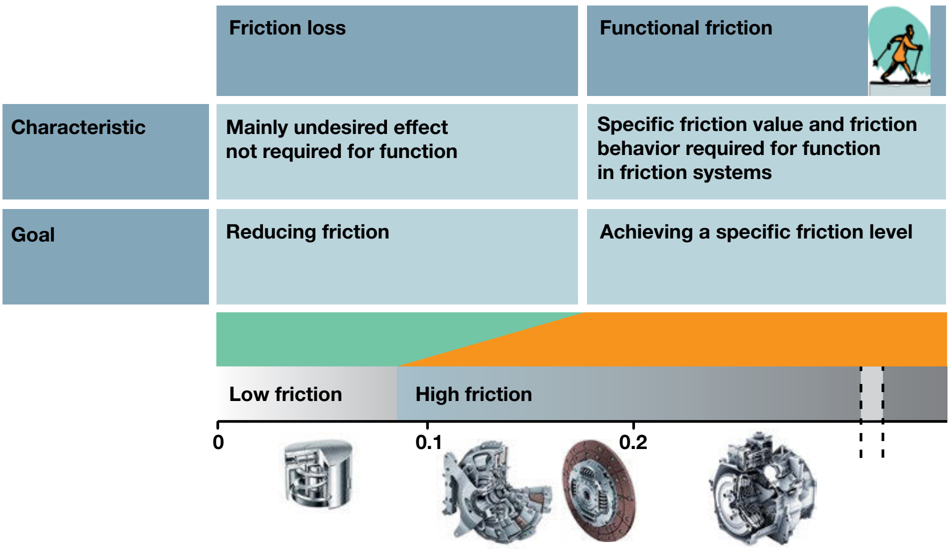

Figure 9 Functional targets on the friction axis with product examples

Functional friction

Similar to the cross-country skier mentioned earlier, friction in an automobile is not always a bad thing. In a bearing, the aim is to minimize friction, in an engaged clutch, a brake, or in a press fit, the aim is to maximize it. Here, friction is used for a very specific purpose. The latter can thus also be called "functional friction" (Figure 9).

Classic application examples of functional friction are clutches with a dry and oil-lubricated design, damping systems such as torsion dampers for clutch disks, and the synchronizing units in the transmission.

Like all systems in an automobile, the tribological system is in line with the downsizing trend, resulting in improved performance: Specified requirements for the friction value must be met with smaller components. In addition to the parameters relevant for tribology, such as the sliding speed, temperature, and pressure, the system environment must be optimized continuously to supply customized friction.

One of the requirements is understanding friction phenomena. Analyses were previously limited to specific dimensions or scale levels; friction phenomena are often analyzed at the machine dynamics level. This means that the friction system is tested for a specific application, and conclusions are drawn from this. However, since friction occurs in the friction contact, the scale levels of contact mechanics must also be taken into consideration, such as the micro, meso, and nano levels. The atomic scale level can be left out here as it is used more for fundamental scientific research.

The consistency of methods and tools across the various scale levels – from materials to production – is an essential component for the detailed analysis and optimization of friction systems. The tools used at Schaeffler range from methods for analyzing systems and data to scale-specific test stands and materials analyses. The experts of the Schaeffler Group work together in an interdisciplinary fashion to use these methods efficiently.

Dry running friction linings for clutches

A dry running double clutch system represents a much greater challenge for the friction materials of the clutch than conventional manual transmissions. Inspections here range from the system level to sub-components and partial lining (Figure 10).

An essential parameter are the comfort properties of the friction material. These are assessed by determining the damping behavior or excitation behavior of the friction material on a judder test stand (Figure 12). These inspections often show that damping decreases as the mean friction value increases; this means that friction vibrations increase. This behavior can be observed for all friction systems and appears to be a universally valid principle. The consistent application of standardized methods and tools has lately achieved considerable success. Figure 11 shows an example: The damping and excitation values were taken from a large number of tests with components that have different load profiles and plotted on a frequency scale. The significant improvement in the friction materials is clearly visible and re-

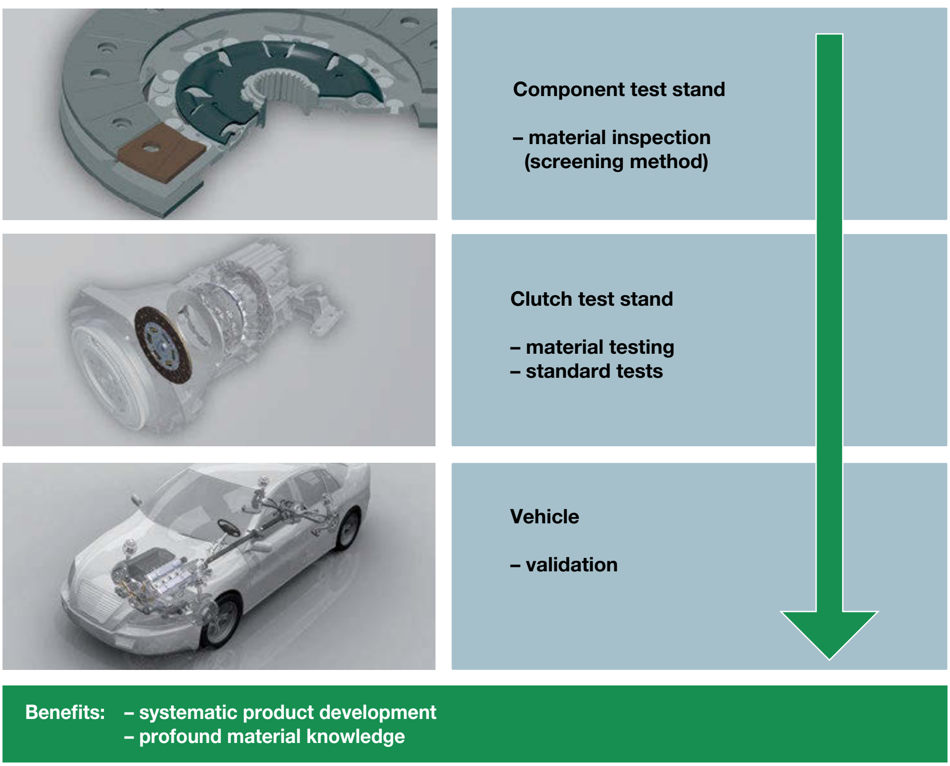

Figure 10 Comprehensive lining development from partial lining investigation to complete clutch

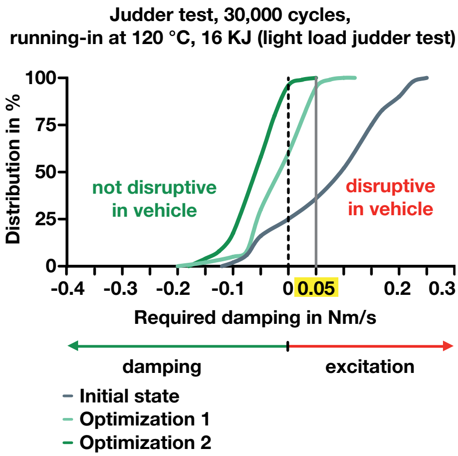

Figure 11 Optimization of lining damping through use of a judder test stand

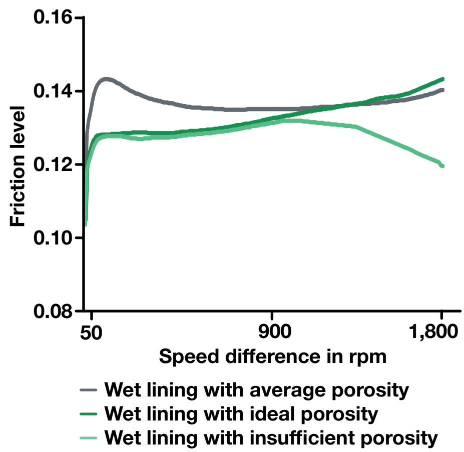

Figure 12 Improvements in friction value behavior through lining porosity

flected primarily in a much lower dispersion. Due to the internal damping of the power train, excitation values of more than 0.05 Nm/s are a disturbance and noticeable for the driver as judder vibrations.

Wet linings for twin clutches

For wet linings, oil is the third tribological component in addition to the lining and steel or cast iron that function as the friction contact surfaces. The oil serves to dissipate the frictional heat, but it can also have negative effects. Too much oil between the friction contact surfaces leads to hydroplaning, similar to the aquaplaning of tires on a road wet with rain, and thus results in a low and uncontrollable friction value. In addition, drag losses occur in open clutches that significantly reduce efficiency. If there is not enough oil, there is a risk of partial mixed friction or even dry friction; this has a considerable impact on comfort behavior. For this reason, the macrostructure of the lining must be designed in a way that permits the oil to be distributed uniformly to the various friction surfaces and to ensure that the aquaplaning effect can be prevented reliably. This is achieved through the use of specific groove geometries. Adequate porosity of the lining supports this effect.

If these and other findings are implemented consistently, the friction value behavior of wet clutches can be improved significantly. Figure 12 shows an example. The correlations described here should suffice to show that the development of an efficient tribological system is only possible if all conceivable boundary conditions have been taken into consideration.

Challenges for friction linings in synchronization

The friction value structure and consistency are important variables in the development of synchronizing materials. The transmission oil must be pushed away quickly from the friction contact to achieve these variables. If the microstructure of the friction materials cannot ensure this, other solutions must be found. One solu-

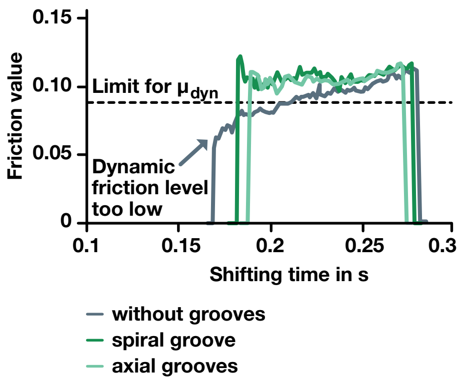

Figure 13 Effect of macro-geometry on the torque curve

tion is the targeted macro-structuring of the friction material by using grooves or groove patterns. The diagram in Figure 13 shows the torque curve of a gear shift mechanism with a friction material with a groove and without a groove. Without the groove, only a very small dynamic initial friction value can be observed. It results in longer shifting times and, in extreme cases, prevents the transmission from shifting altogether.

Modifying the macroscopic surfaces – in this case by means of spiral or axial grooves – can help improve the torque curve. As the oil is pushed away rapidly, the dynamic friction value is already at a much higher level even at the start of the shifting operation, guaranteeing a high level of shifting comfort and short shifting times.

Tribotronics

The term “tribotronics” is used to describe a fairly new field within tribology that integrates mechatronics into a tribological system with the aid of an electronic control system. Mechatronics differs from tribotronics in that it only uses information from the inputs and functional outputs of the mechanical system to control its operation. Such functional outputs supply information about speeds, torques, temperatures and loads.

Tribotronics, on the other hand, not only considers additional output parameters such as friction, wear, or vibrations, but influences them by means of an electronic control system. The goal is to increase the performance, efficiency, and reliability of the tribological system and thus of the entire application. In tribotronics, the component becomes a sensor or actuator – or, put another way: The sensor or actuator becomes a component (Figure 14). This opens up an entirely new range of applications for coating technology.

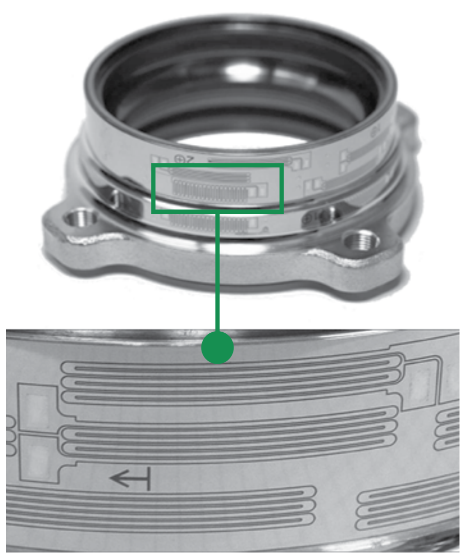

Figure 14 Sensotect® coating measures the force on the rolling bearing. The component becomes a sensor.

Its new thin-layer sensor Sensotect® provides Schaeffler with a basis for implementing tribotronics in automotive engineering and industrial applications. Going forward, this will permit output parameters such as the force, torque, and temperature of a component to be measured in places where conventional sensors, such as glued strain gauges, cannot be used because they are susceptible to material aging or signal drifting due to polymer glues or transfer foil.

With Sensotect®, a thin, strain-sensitive PVD coating performs the actual measurement function. The coating is structured by micromachining. These structures are deformed at the same rate as the carrier component. Deformation results in a change in electrical resistance in the sensor layer. This change is a measurement, for instance, of the contacting torque or the forces impacting on thrust bearings, drive shaft, or steering column shafts. Measurements are taken during continuous operation and with extreme levels of sensitivity and precision, or, to be more precise, with minimal hysteresis errors and minimal linearity deviations. Schaeffler has already been able to show the function of this type of sensor system in demonstration vehicles – both in passenger cars and bicycles.

One of the greatest challenges of such sensory coating systems is manufacturing. The use of highly efficient coating sources and compliance with very stringent requirements for cleanliness in the manufacturing process has helped Schaeffler to achieve a quality level even for typical three-dimensional rolling bearing components that was previously known only for planar substrates in the semiconductor industry.

In the continued development of tribotronics, Schaeffler focuses on processing signals from surface sensors in an external control unit. Based on tribological algorithms, these signals are used to perform calculations that indicate whether the operating temperature of the component has to be corrected or whether a dimensional change is required, to name just two examples. Actuator coating systems carry out the necessary corrections. Completely autonomous and self-regulating systems are feasible if additional functions are integrated into the component surface, such as telemetric components or transfer structures for energy supply and energy production.

Summary and outlook

The optimization of tribological systems in drives still offers considerable potential for reducing fuel consumption. Opportunities can be found in the selection of an optimum bearing system as well as a coating customized for a specific application. Customized, nano-structured diamond-like Triondur® DLC coating systems can help optimize sliding contacts in such a way that their friction losses occur in the same range as rolling friction. The new Triondur® coating systems help mechanical bucket tappets achieve friction values that are almost identical to those of a roller finger follower. At the same time, coating offers excellent wear protection – without requiring additional design space. Since these systems cannot be calculated analytically, Schaeffler has broken new ground in their development: Data mining is combined with an artificial neural network to generate a procedure that can predict the tribological behavior of such complex tribological systems.

At the other end of the imaginary “friction axis”, one of the development goals is to produce the required friction values with components that continuously decrease in size and weight. The analysis of friction phenomena must be expanded to include all dimensions and scale levels in order to achieve the best results from a system evaluation.

Tribotronics opens up an entirely new range of applications for coating technology. In future, the combination of force converters, data transfer, and transfer structures for energy supply and energy production will make autonomous measurement systems a possibility even for rotating parts.

Schaeffler has combined all of the important expertise, from fundamental tribological research, coating development, and coating facility engineering to volume production and quality control measures. The most important goal here is to derive the best integrated surface technology-based solution from customer requirements so that the customer is provided with a product that has a significant added value – and with the best quality.

Literature

[1] Musayev, Y.: Verbesserung des tribologischen Verhaltens von Stahl/Stahl Gleitpaarungen für Präzisionsbauteile durch Diffusionschromierung im Vakuum. Friedrich-Alexander-Universität Erlangen-Nürnberg, Dissertation, 2001

[2] Czichos, H.; Habig, K.: Tribologie-Handbuch. Reibung und Verschleiß. 2. Auflage. Wiesbaden: Vieweg, 2003

[3] Hosenfeldt, T.; Musayev, Y.; Christgen, W.: Energieeffizienz durch Reibungsreduzierung mittels Oberflächentechnik als Konstruktionselement. 2. ATZ-Fachtagung Reibungsminimierung im Antriebsstrang, 2011

[4] Schulz, E.; Musayev, Y.; Tremmel, S.; Hosenfeldt, T.; Wartzack, S.; Meerkamm, H.: Reibung und Verschleiß vorhersagen - Durch neue Methoden der virtuellen Produktentwicklung Schmierstoff und Schichtsystem optimal aufeinander abstimmen. mo – Magazin für Oberflächentechnik 65, 2011, no. 1-2, pp. 18-21

[5] Hosenfeldt, T.; Musayev, Y.; Schulz, E.: Customized Surface Technology – A Modern Design Element to Increase Energy Efficiency by Friction Reduction, VDI Fachtagung Ventiltrieb und Zylinderkopf, 2012